Energy Production and Performance of a Wind-Driven Induction Generator

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ABSTRACT

A modern wind turbine, an Enertech Model 44/25*, was installed on May 26, 1982, at the USDA Conservation and Production Research Laboratory, Bushland, TX. The wind machine, acquired for a determination of agricultural applications, had a 25-kW induction generator which provided 240 V, 60 Hz, single-phase electric power. The horizontal-axis wind turbine had a 13.4-m diameter, three-bladed, fixed-pitch rotor and was mounted on a 24.4-m tower. The blades were laminated epoxy-wood attached to a steel hub.

The wind turbine operated 64% of the time, and was available for operation over 95% of the time. The unit had a net energy production of over 100,000 kW·h for a 20-month period in an average windspeed of 5.9 m/s at a height of 10 m. Power curves were established for the wind turbine at two different pitch settings and with two different sets of blade-tip brakes.

INTRODUCTION

The United States Department of Agriculture, Agricultural Research Service (USDA-ARS) has been studying the use of wind energy to generate power for farming and rural applications. Research has been conducted to determine the reliability and performance of wind machines for agricultural applications. The matching of the wind turbine output to the load has been a major element in these studies. The service and maintenance requirements of equipment and the reliability of wind systems over extended periods of time has also been examined.

Beginning in 1976, USDA-ARS initiated several studies using state-of-the-art wind machines. These machines utilized either DC generators with inverters or synchronous generators to produce electricity. Wind machines using these types of generators or alternators require speed regulation, normally provided by a mechanism to vary the rotor blade pitch or a tail to swing the rotor out of the wind. This speed control was required to limit the power and avoid overloading the generator (Park, 1981). As wind turbine sizes increased, the variable pitch mechanism became more complicated and costly, and tails became too large to control. Golding (1976) indicated that the induction generator would be superior to the synchronous generator because of its greater stability, robustness, and ease with which it could be made to operate automatically.

The induction generator is essentially an AC motor that is operated above its synchronous speed. The normal induction generator requires excitation from the utility, while its output matches the voltage and frequency of the utility. It has the advantages of low cost and low maintenance while having the ability to operate as a motor. Disadvantages include that it normally requires a speed increaser, operates at a nearly constant rotor speed, and has a low power factor (Jayadev, 1976).

Prior to 1980, induction generators were used only in small wind turbines, and mainly by two manufacturers. The wind turbine used in this study contained one of the largest induction generators used in 1982. The wind turbine was manufactured by Enertech Corporation, Norwich, VT, and was a design scaled-up from a 4-kW unit. The use of induction generators has greatly increased, and in 1984, over 90% of wind systems sold are of the induction generator type.

Installation of the Enertech Model 44 at Bushland, TX, was completed on May 26, 1982. The machine was operated on a "shakedown" basis until June 14, 1982, at which time the unit was placed in full-time operation.

WIND TURBINE DESCRIPTION

The horizontal-axis wind turbine had a 13.4-m diameter, three-bladed, fixed-pitch rotor mounted on a 24.4-m free-standing tower. The blades were fabricated from laminated epoxy-wood attached to a steel hub. Table 1 is a listing of the specifications of the wind energy conversion system.

The Enertech 44/25 produced utility-compatible electrical power by employing a 240 V, single-phase induction generator. Capacitors of 160 μF were installed with the 25-kW generator to improve the power factor and generator efficiency. Slip-rings were used to transmit the power from the generator down the tower to the utility connection.

The wind turbine was primarily controlled by a signal from an anemometer. The rotor was held stationary by a brake at windspeeds below that to produce power. When the control system determined there was adequate wind, the brake was released and the generator was utilized as a motor. The wind turbine was "motored" for approximately 15 seconds, and then the wind further accelerated the rotor to its operational speed. The rotor's rotational speed was sensed by a magnetic tachometer. When an operational speed was sensed, the generator was connected to the utility grid. If the windspeeds dropped below that to produce power, the generator was disconnected from the utility grid and the brake was

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*Mention of a trade name or product does not constitute a recommendation or endorsement for use by the U. S. Department of Agriculture but is given for informational purposes only.

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TABLE 1. SPECIFICATIONS OF ENERTECH 44/25 WIND TURBINE, SERIAL NO. 2, AT BUSHLAND, TEXAS (ENERTECH, 1981).

System	
Type	Utility interface
Axis of rotor	Horizontal
Location of rotor	Downwind
Number of blades	Three
Centerline hub height	25 m
Rotor	
Rotor type	Fixed pitch
Rotor speed at rated power	53 rpm
Blade tip speed at rated power	37.2 m/s
Blade material	Wood/epoxy laminate
Blade length	6.7 m
Transmission	
Type	Triple reduction, helical
Ratio	1:34.5
Generator	
Type	Single-phase, induction generator
Rated power	25 kW
Output voltage	220/240 VAC
Yaw System	
Yaw control	None, rotates freely 360 degrees
Rotor Speed Control	
Normal operating speed	Aerodynamic stall
High windspeed shutdown	Control system applies brake
Emergency rotor overspeed	Blade-tip brakes deploy
Tower	
Type	Galvanized self-supporting truss type
Height	24.4 m
Performance	
Rated power	25 kW at 13.4 m/s
Start-up windspeed	4.9 m/s
Shut-down windspeed	3.6 m/s
Cut-out windspeed	22.3 m/s
Design survival windspeed	53.6 m/s

applied. The control system also activated the brake and disconnected the generator from the utility grid in the event of a grid power failure or when winds averaged over 22 m/s for 45 s. The control system automatically restarted the machine when power was restored or when winds dropped to an average of 16 m/s. The control system was located near the base of the wind turbine.

PERFORMANCE DATA

The machine was initially operated with a blade pitch offset of minus-two degrees (referenced to the blade tip flat bottom, with respect to the rotor plane) (Zickefoose, 1982) to reduce the loading on the gearbox, generator, and brakes. After a new brake was installed, it was determined that a higher power output could be reached without overloading the system. On March 1, 1983, the blade pitch was changed to minus-one degree. Blade-tip brakes (aerodynamic brakes), with a modified design, were installed on July 7, 1983.

Power curves, shown in Fig. 1, were established for the wind turbine when the blade pitch setting was minus-two degrees and minus-one degree with the original tip brakes. Data, sampled at 4.5 times per second with a 15-second average, were utilized to produce the power curves. The data were corrected to an air density of 1.226 kg/m^3 which represents standard density (sea level at 15 °C). Reactive power varied from 2.9 kVARs (reactive kVA) at cut-in to 13.2 kVARs at the rated real power of 25 kW. The cut-in windspeed was the same for both pitch settings. Maximum power observed was 23.2 kW, with a pitch of a minus-two degrees and 29.3 kW with a pitch of a minus-one degree. A pitch setting of a minus-one degree is recommended by the manufacturer for Bushland, TX (Zickefoose, 1982).

The change in system efficiency obtained by modifying

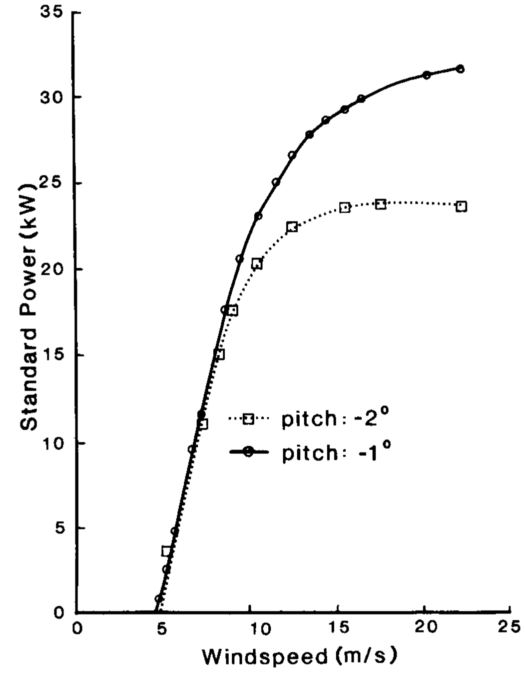

Fig. 1—Power curves of Enertech 44/25 corrected to standard air density with original tip brakes.

the design of the blade-tip brakes is shown in Fig. 2. System efficiency was calculated using the electrical power output at the control system versus the available power in the wind. The system reached a peak efficiency of 31.3% at a windspeed of 7.5 m/s, with the original tip brakes. The peak efficiency was higher, 34.2% at 6.5 m/s, with the revised tip brakes. The tip speed was approximately 37 m/s allowing the rotor to reach its best efficiencies at relatively low windspeeds. The revised tip brakes increased the performance at lower windspeeds while not changing the performance at moderate and high windspeeds.

The power curve data for a pitch setting of a minus-one degree was utilized to predict the annual energy output of the wind turbine using a Rayleigh probability distribution for windspeed. These predicted annual energy outputs of the wind system are shown in Fig. 3. The slight increase in performance of the revised tip brakes at lower windspeeds increased the total energy output of the wind turbine from 4 to 7%. At an annual mean windspeed of 6.0 m/s, the wind system with revised tip brakes had 6% greater output. Energy output was

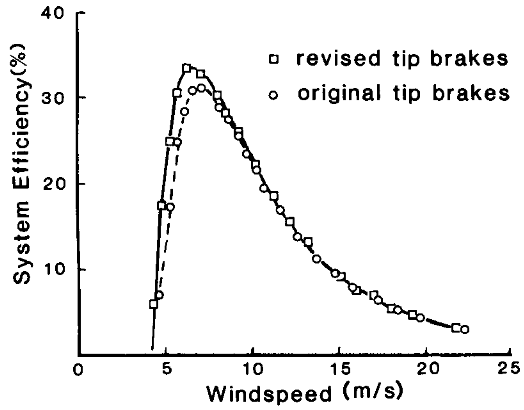

Fig. 2—System efficiency of Enertech 44/25 with blade pitch offset minus-one degree.

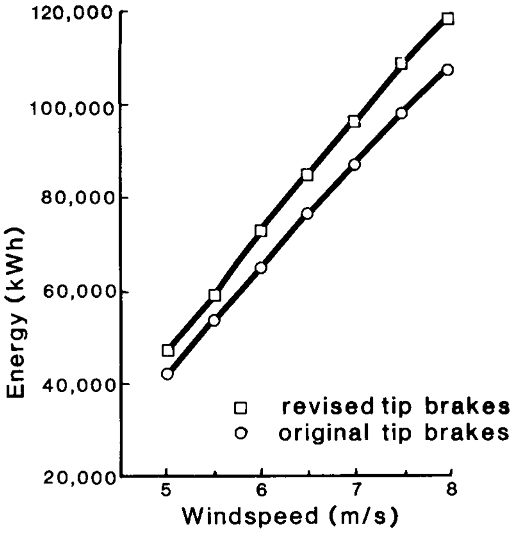

Fig. 3—Predicted annual energy production of Enertech 44/25 with blade pitch offset a minus-one degree, air density of 1.226 kg/m³, and an availability of 95%.

increased moderately because windspeeds between 5 and 10 m/s occur more frequently than windspeeds above 10 m/s.

The Enertech 44/25 operated over 9,500 h and produced over 100,000 kW·h of energy for the 20 months from June 14, 1982, through February 15, 1984. Average net power production of the wind turbine on a monthly basis is shown in Fig. 4 for the time period. Average net power is equal to the total energy produced minus the energy consumed by the generator divided by the time period in hours. Energy data were collected from two detented utility meters. The wind turbine was operating when the generator was connected to the utility grid. The average net power represents the energy production over the time period; however, the average net power while the system is operating is more useful when matching the system to a specific load. Average net power for the entire period was 6.9 kW while the average net power when operating was 10.8 kW. The average net power production was 7.8 kW over the period when the blade

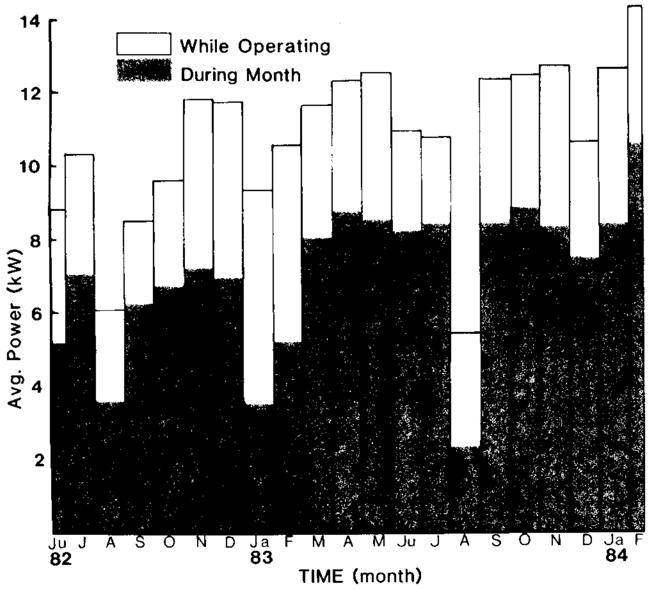

Fig. 4—Average power production of the Enertech 44/25 at Bushland, TX, from June 14, 1982, through February 15, 1984.

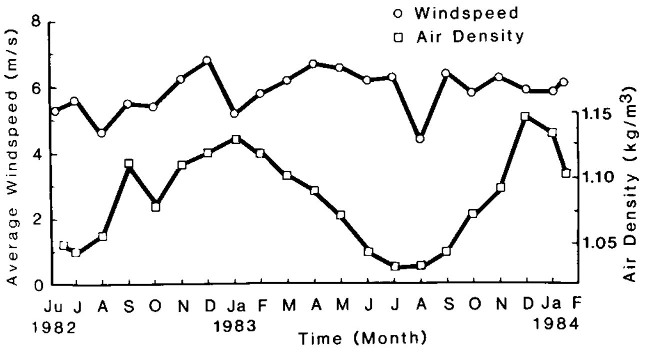

Fig. 5—Windspeed and air density at Bushland, TX, from June 14, 1982, through February 15, 1984.

pitch was a minus-one degree. Monthly average windspeed and air density during the entire test period are shown in Fig. 5. The average windspeed was 5.9 m/s at a height of 10 m, with an average air density of 1.085 kg/m³. The wind turbine operated 64% of the time and was available to operate over 95% of the time. Availability is defined as time the machine was operating or could operate, if there had been adequate meteorological conditions.

Fig. 6 shows power and windspeed duration curves, developed from 5-min averages, for continuous data from October through December 1983. The percentage of time which the power was greater than the value given is represented by the curve. The wind turbine produced its rated power of 25 kW or greater only 5% of the time. The machine was on and producing more than 1 kW, 65% of the time. The average windspeed was 5.6 m/s at a height of 10 m while the average air density was 1.098 kg/m³ for the three months.

ECONOMICS

The economics of collecting energy from the wind is dependent on several factors which can fluctuate depending on the specific application. The cost of energy produced from the Enertech 44/25 was calculated from the following equation (Ramler and Donovan, 1979):

$$COE = [(IC)\ (FCR) + (AOM)]\ /AKWH$$

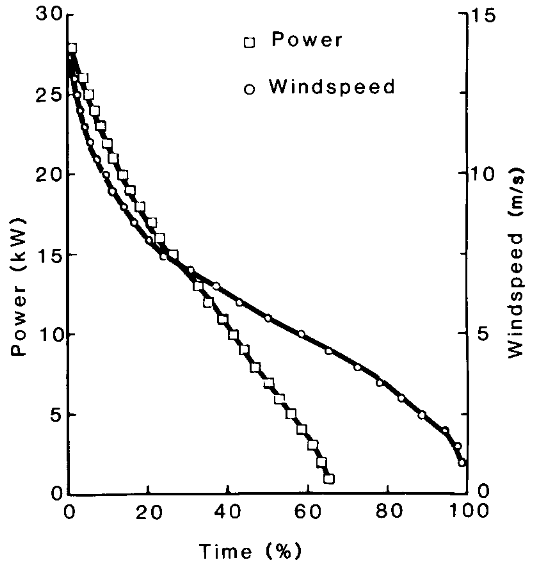

Fig. 6—Power and windspeed duration for Enertech 44/25 from October through December 1983.

where:

COE = the cost of energy, cents/kW·h
IC = the initial installed cost, $
FCR = the fixed charge rate, %/year
AOM = the annual operation and maintenance, % of IC/year
AKWH = the net annual kW·h energy production, kW·h/year

The initial cost of the system was $36,500, with an additional $3,500 for installation. A payback period of 10 years was selected with an annual rate of interest of 12%, which results in a fixed charged rate of 17.2%. Annual operation and maintenance was assumed to be 2% of the initial cost which is $800. An annual net energy production of 60,000 kW·h was used. The cost of energy with the preceding data was calculated to be 12.8 cents/kW·h.

Sensitivity curves are helpful in locating the areas most responsive to the cost of energy (Fig. 7). Two of the most critical factors were initial cost and energy production. The initial cost is a function of mass production, government credits, and several design features. Energy production is directly affected by the windspeed and air density at the specific location and the availability of the machine. A 15% decrease in initial cost or a 20% increase in energy production would result in a drop of 2 cents per kW·h in the cost of energy.

OPERATING EXPERIENCES

The Enertech 44/25 has operated in temperatures below −18 °C and above 38 °C. Gusts of wind greater than 31 m/s have been experienced while the machine has been operating. The wind turbine has successfully shut down as designed with windspeeds gusting to 25 m/s.

The unit was available to operate over 95% of the time from June 14, 1982, through February 15, 1984. Table 2 is a list of the total time lost due to either service or repairs of the wind turbine. Included in the table is an estimation of the run time lost due to mechanical problems or servicing.

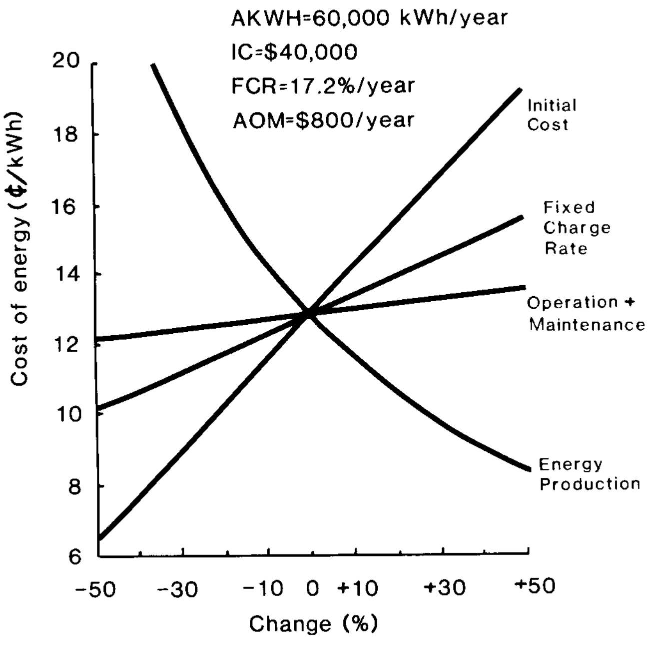

Fig. 7—Sensitivity diagram for cost of energy from Enertech 44/25.

All maintenance and service was accomplished by USDA-ARS personnel. The major servicing task was the insertion of a new brake. The original brake using a hydraulic pump was not adequate because of overheating and a Stearn's* brake was inserted in its place. A Stearn's brake is a multiple plate-type disc brake that is spring-actuated. The brake change was accomplished with the use of a crane with two cables, one for equipment and the other to carry personnel.

Storms producing ice on the blades occurred three times in the Spring of 1983. The blades were covered with ice before the anemometer, which is used to signal the control system, was covered. The generator operated as a motor and consumed substantial amounts of energy because the control system could not sense negative power. Cold weather also caused problems with the start-up of the turbine. For temperatures below 0 °C, the "motoring" time had to be increased to 20 s by adjusting a manual setting inside the control box. A control system, based on a single anemometer signal, can have difficulties in operating properly in abnormal circumstances. The loss of a cup from the anemometer or a reduction in windspeed because of the tower can have undesirable results. The monitoring of current output of the generator would alleviate most problems.

The majority of downtime was attributed to faulty magnetic tachometers used for measuring rotor rotational speed. These failures were responsible for 427.5 h or 61% of the total downtime. On November 21, 1983, the magnetic tachometer failed and the rotor went into overspeed. The blade-tip brakes were improperly set and failed to deploy. A tip brake was thrown before personnel stopped the machine with the conventional brake. Acquisition of magnetic tachometers accounted for the major portion of the downtime. The slip-ring assembly has also been a trouble area. Newer versions of the Model 44 eliminated both problems areas. The rotor is "motored" to operational speed without any switching. The need for monitoring the rotor rotational speed in the control box and adjusting the "motoring time" has been eliminated. The slip-ring assembly has been replaced with flexible cable that can be twisted.

Problems that require small amounts of time to repair can account for a significant amount of downtime. An example of this would be the failure of the brake control relay which occurred on August 19, 1983. It was August 22 before a turbine malfunction was discovered. It required ten minutes to locate the problem and repair the relay by tightening a screw. A wind turbine needs to be monitored at least once daily.

SUMMARY AND RECOMMENDATIONS

The Enertech 44/25 operated over 9,500 h and produced over 100,000 kW·h of energy in a 20-month period. Although this wind turbine was only the second commercial machine of its design, it was available to operate over 95% of the time. With greater access to spare parts and more operating experience, the machine may be capable of even higher availability.

Agricultural technicians who had been trained to maintain the Enertech 44/25 were able to handle most of the service needs. A wind turbine needs to be monitored on a daily basis to maintain a high degree of availability.

The changing of the blade pitch showed how important it is to have the proper pitch adjustment. A

TABLE 2. SUMMARY OF DOWNTIME FOR THE ENERTECH 44/25 FROM JUNE 14, 1982, THROUGH FEBRUARY 15, 1984.

Year	Date	Problem	Downtime	Estimated run time lost
			--------- hours	------
1982	Aug. 20	Inspection and installation of safety climbing cable	2.0	0.0
	Sept. 24	Blade-tip brake test	1.0	1.0
	Oct. 4	Adjustment of blade-tip brake	5.0	3.0
	Oct. 23-27	Inspection by manufacturer personnel	8.5	7.0
	Nov. 12	Break in wire to rotor rpm sensor	15.0	15.0
1983	Dec. 29-31 Jan. 1-4	Starting time and broken control relay	130.0	85.0
	Jan. 10-11	Installation of new brake	26.0	10.0
	Feb. 11-18	Rotor rpm sensor failure	166.0	106.0
	Mar. 1	Blade pitch change	3.0	0.0
	Mar. 16	Overload relay undersized	14.0	14.0
	Apr. 1	Replacement of overload relay	0.5	0.5
	May 19	Replaced anemometer	0.3	0.0
	June 8	Change fluid in gearbox and yearly maintenance	2.5	0.0
	July 7	Replace blade-tip brakes	3.0	0.0
	Aug. 19-22	Brake control relay malfunction	58.0	31.0
	Aug. 29-Sept. 6	Rotor rpm sensor failure	203.5	161.0
	Nov. 21-23	Rotor rpm sensor failure Blade-tip brake failure	58.0	38.0
	Nov. 25-Dec. 8	False deployment of blade-tip brake	3.5	3.0
1984	Jan. 13	Replacement of rotor rpm card	0.5	0.5
	Jan. 25	Inspection by manufacturer personnel	0.8	0.8
Total			701.1	475.8

1-deg change on this fixed-pitch machine resulted in over a 25% increase in maximum power production. Wind turbines that are designed with adjustable pitch settings would be beneficial because the pitch could be changed to maximize energy production in regard to the wind regime and elevation. Redesign of the blade-tip brakes had a positive influence on overall energy production.

Data averaged over five-minutes intervals were collected for the power output of the wind turbine over a three-month period. The wind turbine produced its rated output for only a small part of the time. Load matching is required if an agricultural application is to utilize a significant portion of the energy produced.

The Enertech 44/25 is a state-of-the-art wind energy system. With the further improvement of design and manufacturing technology, wind turbines are capable of producing substantial power for agriculture.

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